

Topical Group TF06: Theory Techniques for Precision Physics

Co-conveners: Radja Boughezal (ANL), Zoltan Ligeti (LBNL)

<https://snowmass21.org/theory/precision>

Radja Boughezal

Snowmass Community Summer Study, July 17-26, Seattle 2022

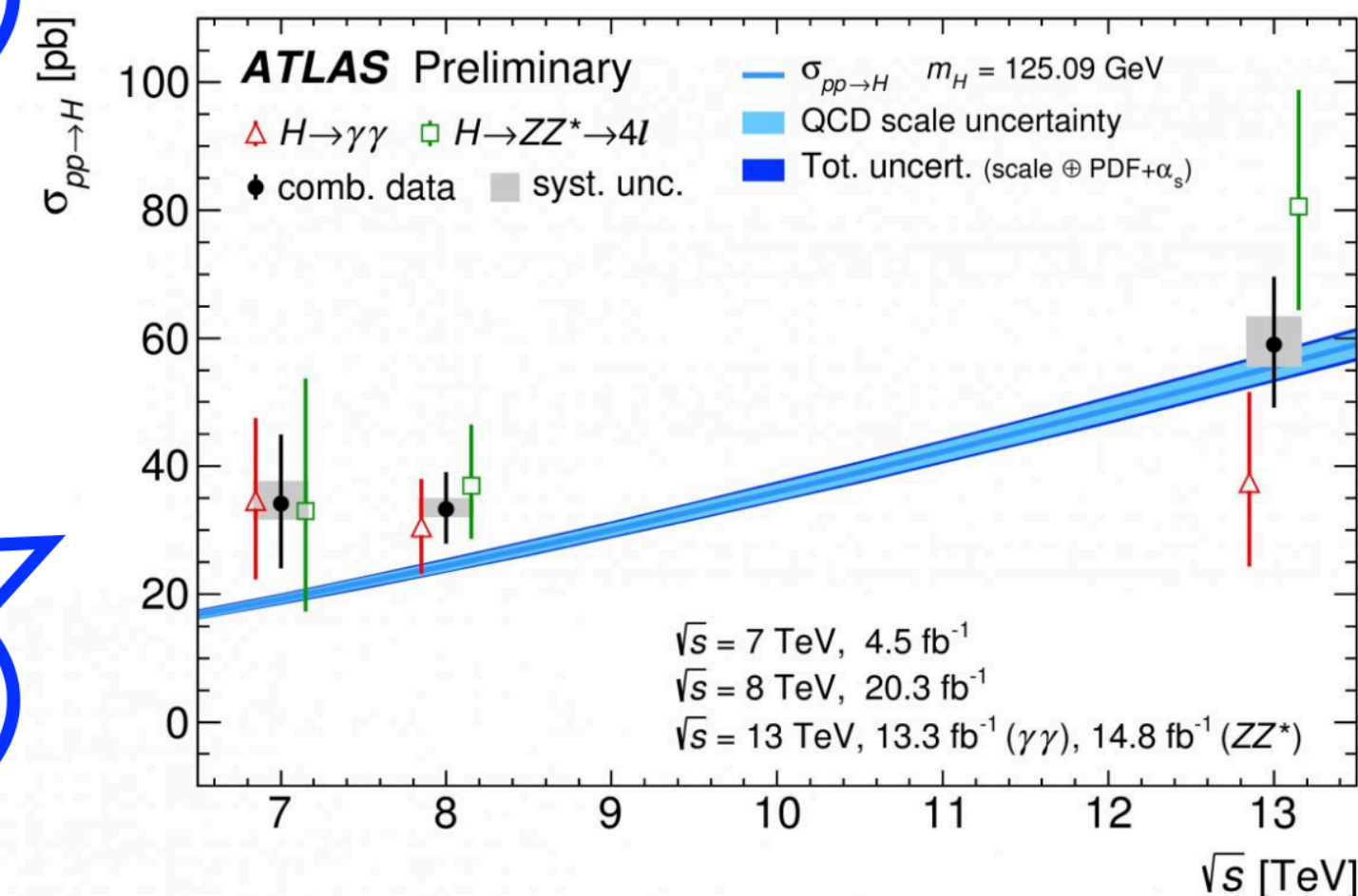
Precision Theory for HEP

- Precision theory has a **dual role** in HEP: leads to new ideas that motivate experimental studies, and supports the experimental program in its search for new physics.
- Inherently **multidisciplinary**: ties together advanced mathematics and high-performance computing with HEP theory and experimental measurements.
- **Focus of TF06**: survey theoretical techniques that enable current and planned precision measurements; discuss novel theoretical developments that may open the door to new levels of theoretical understanding.

Higgs production cross section as an example of all the required advances for a precision prediction

Electroweak corrections @ 2loops

PDFs @ NNLO

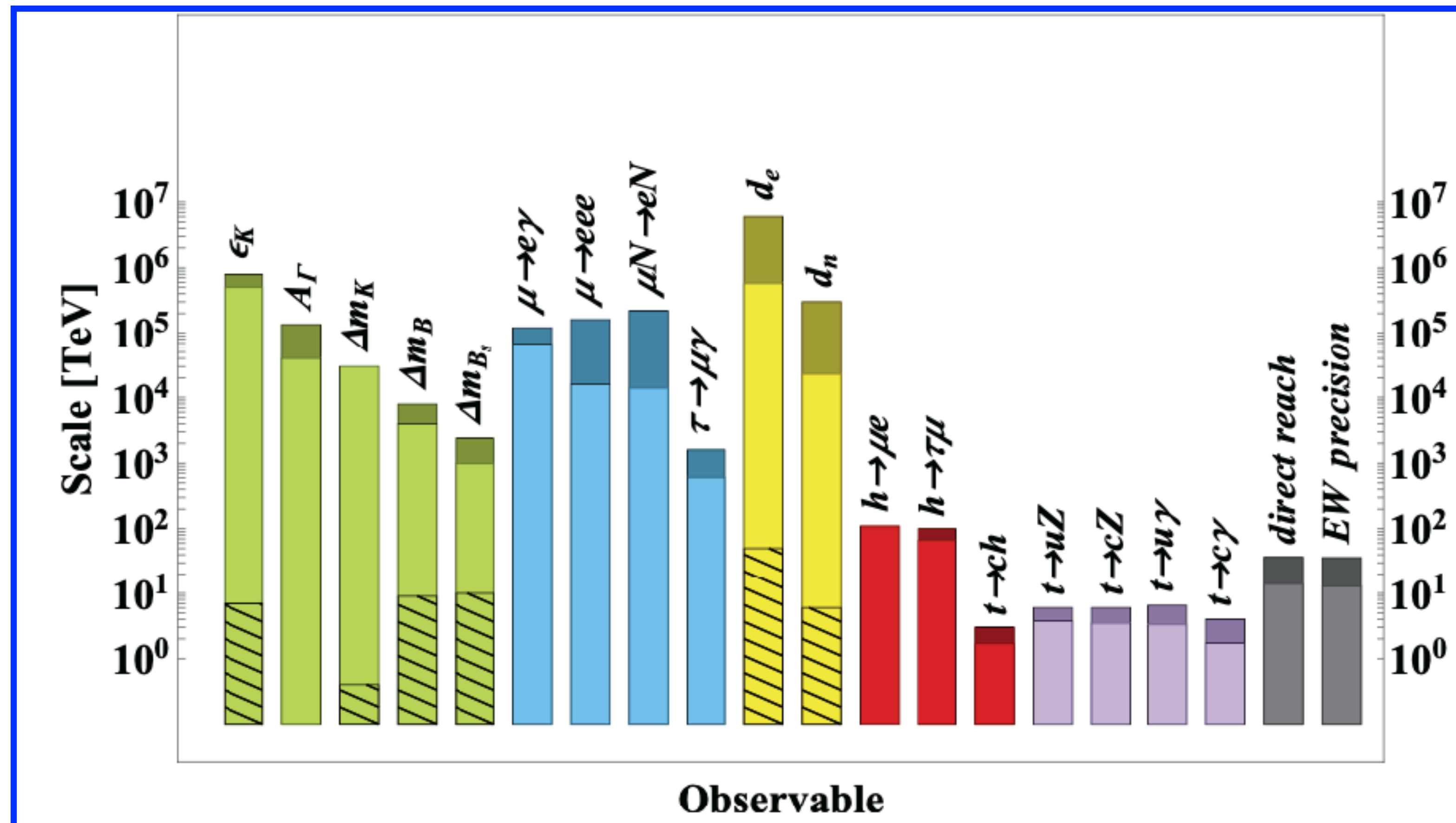


QCD@N³LO

Precision extraction of α_s

Flavor physics

- Flavor physics measurements probe extremely high scales, and severely restrict BSM theories. All flavor measurements rely upon precision theory inputs: precision QCD and electroweak loop corrections, calculations in EFTs such as HQET and SCET, as well as lattice QCD.



Topics covered in TF06

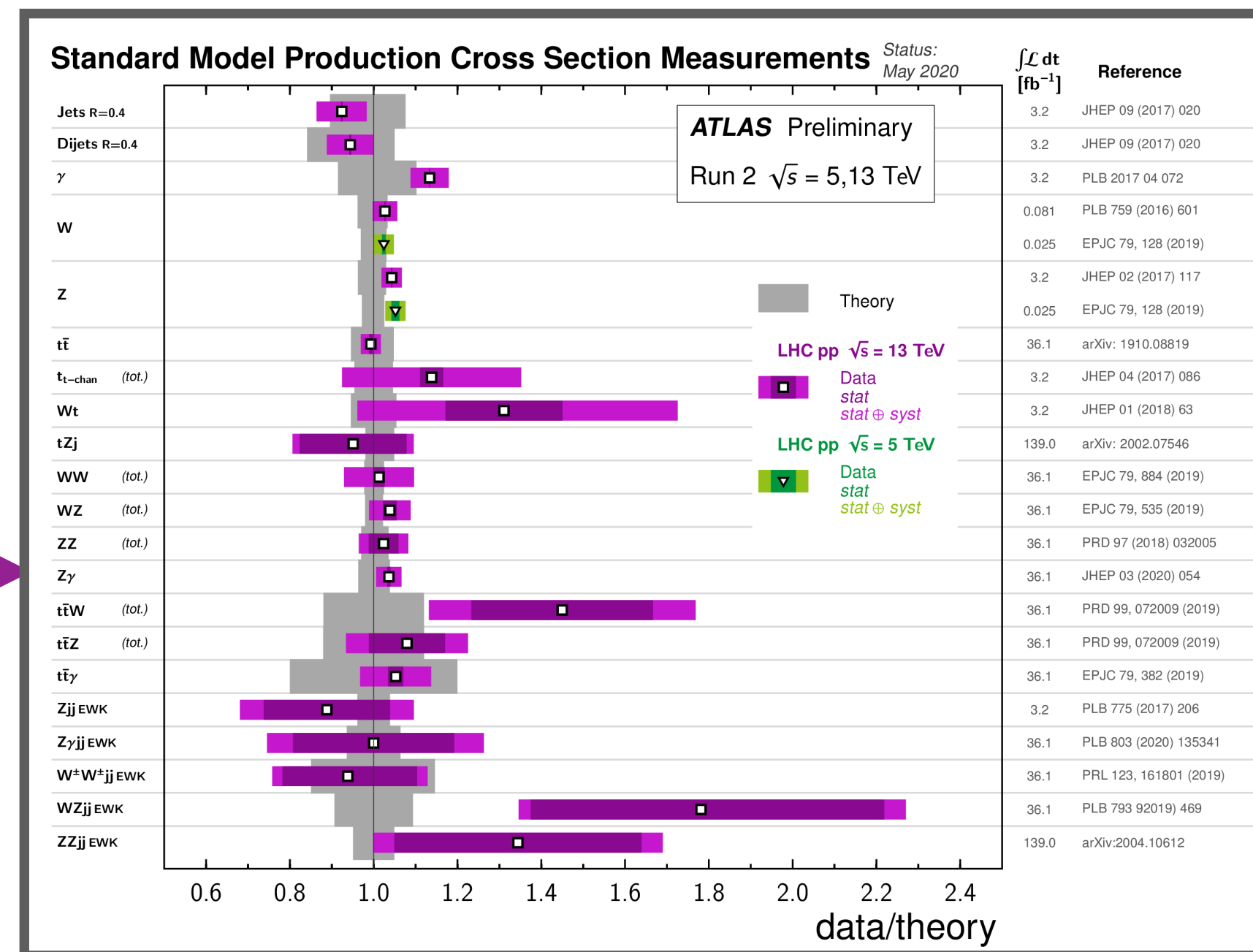
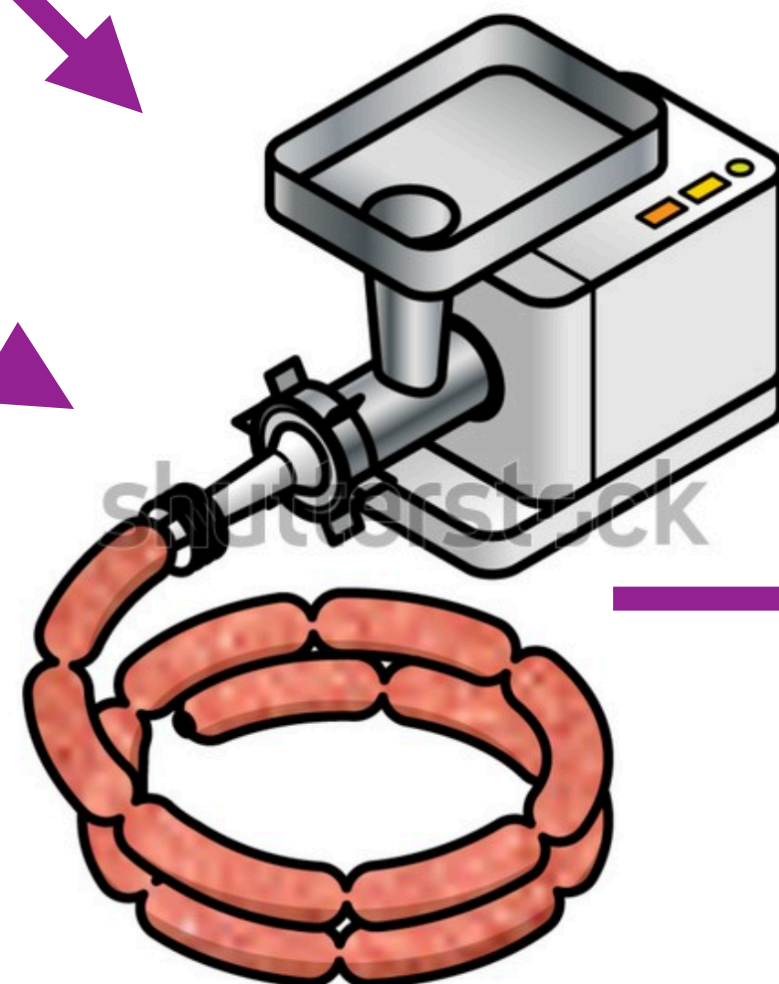
Advances in amplitudes

Multi-loop calculations

EFTs for new physics sensitivity

Monte Carlo event generators

Precision flavour physics



Enable current and planned precision measurements

Motivate new observables with enhanced sensitivity to new physics

A broad variety of theoretical ideas and tools are vital to the success of our precision explorations for new physics !

Contributed white papers

- TFo6 received six white papers reviewing important research directions in the field which formed the basis of our summary report:
- The path forward to N₃LO: [Caola, Chen, Duhr, Liu, Mistlberger, Petriello, Vita, Weinzierl](#)
- Resummation for future colliders: [van Beekveld, Jaskiewicz, Liu, Neill, Penin, Ringer, Szafron, Vernazza, Vita, Wang](#)
- Proton structure at the precision frontier (joint with the Energy Frontier): [Amorso et al](#)
- Future prospects for parton showers: [Darvishi, Isaacson, Masouminia, Nagy, Richardson, Soper](#)
- Theoretical developments in the SMEFT at dimension-8 and beyond: [Alioli, Boughezal, Can, Durieux, Graf, Henning, Kitahara, Li, Lu, Machado, Martin, Melia, Mereghetti, Murayama, Murphy, Roosmale Nepveu, Pal, Petriello, Shadmi, Shu, Weiss, Xiao, Yu](#)
- New physics in B meson mixing - future sensitivity and limitations: [Charles, Descotes-Genon, Ligeti, Monteil, Papucci, Trabelsi, Vale Silva](#)

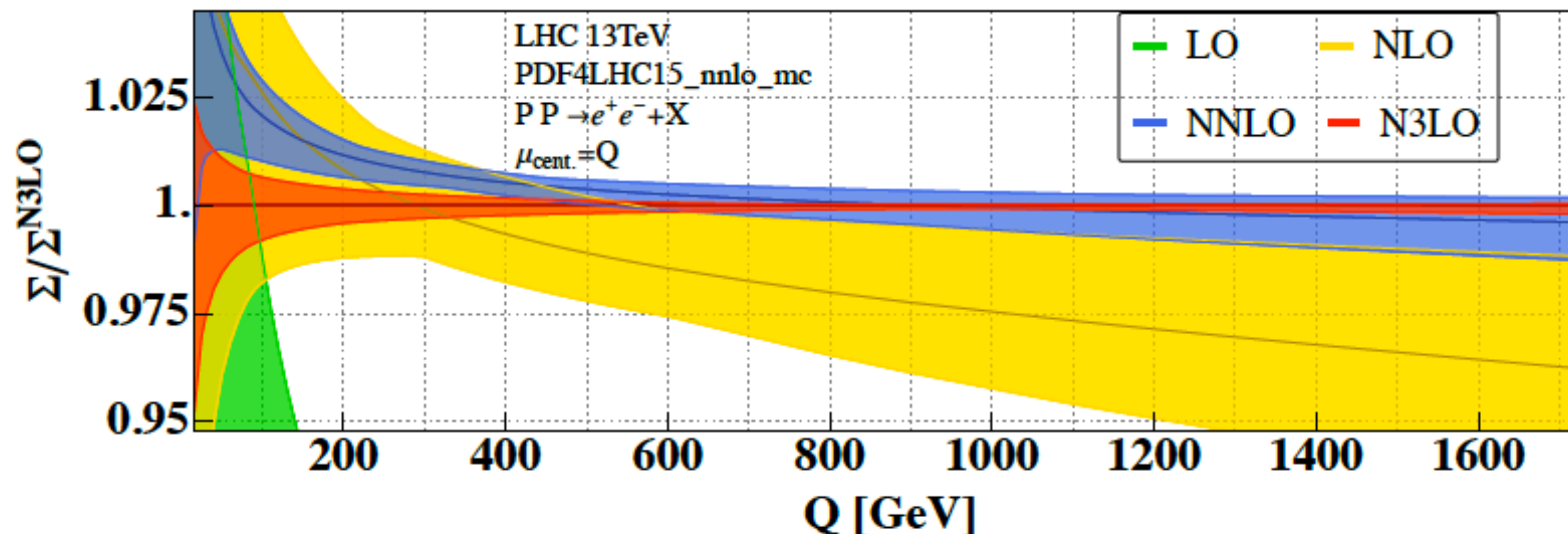
We thank all the white papers contributors for their input!

The Path forward to N³LO

Fabrizio Caola¹, Wen Chen², Claude Duhr³, Xiaohui Liu⁴,
Bernhard Mistlberger⁵, Frank Petriello⁶, Gherardo Vita⁵, Stefan Weinzierl⁷

- Where we are today on the path to establishing the SM at the LHC at 1%:

Duhr, Mistlberger, 2021



Residual scale dependence below 1% over most of the phase space!

The Path forward to N³LO

Fabrizio Caola¹, Wen Chen², Claude Duhr³, Xiaohui Liu⁴,
Bernhard Mistlberger⁵, Frank Petriello⁶, Gherardo Vita⁵, Stefan Weinzierl⁷

- Issues highlighted for future directions:
 - Corrections beyond QCD: accounting for non-vanishing quark masses, mixed QCD-EW effects
 - Factorization violation at N₃LO and beyond
 - DGLAP evolution at 4-loops
 - PDFs at N₃LO
 - Combining fixed-order perturbative predictions with parton showers
 - A better way to estimate theoretical uncertainties

Snowmass 2021 White Paper: Resummation for future colliders

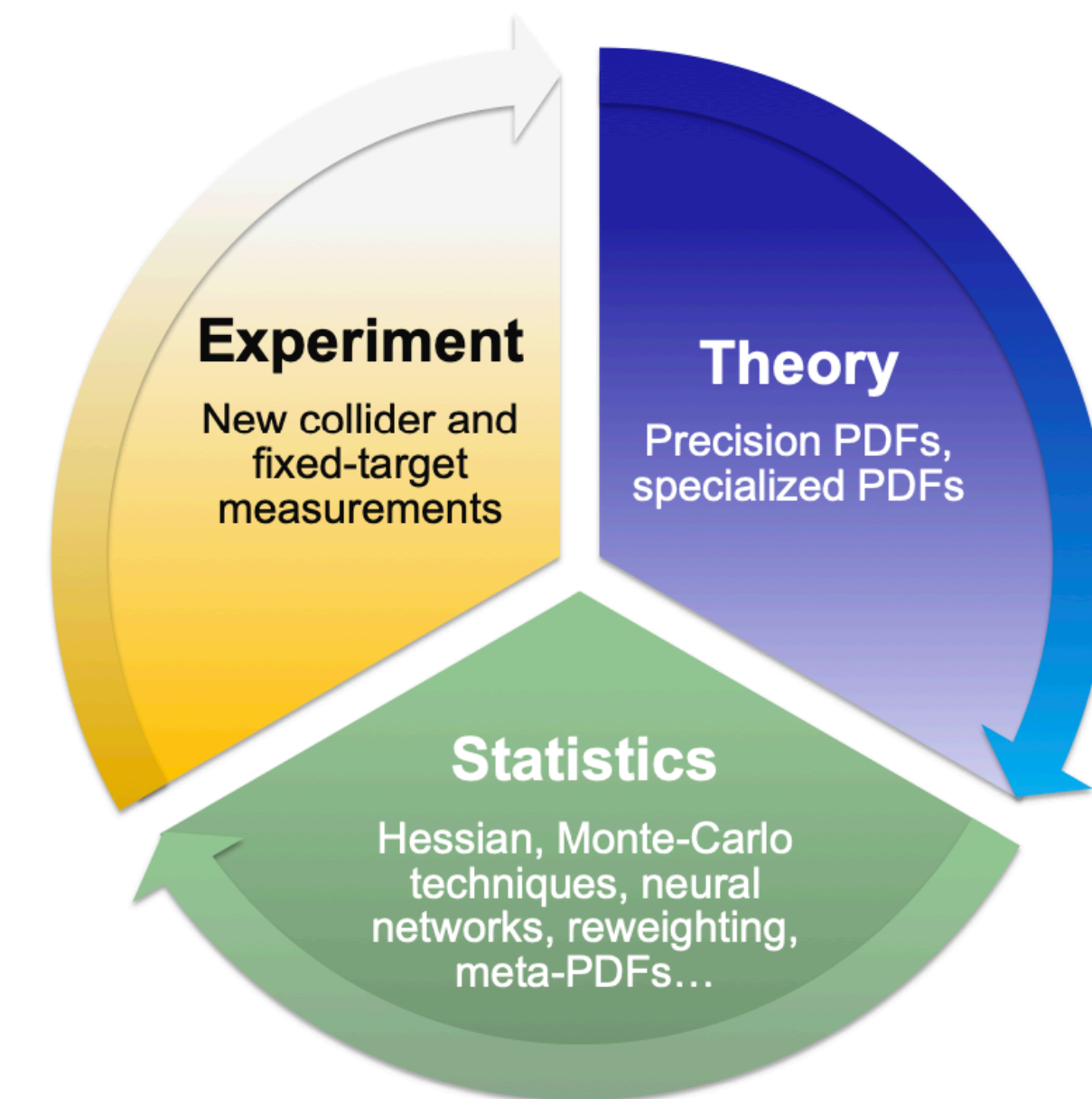
Melissa van Beekveld,^a Sebastian Jaskiewicz,^b Tao Liu,^{c,d} Xiaohui Liu,^{e,f} Duff Neill,^g
Alexander Penin,^h Felix Ringer,^{i,j} Robert Szafron,^k Leonardo Vernazza,^{l,m} Gherardo
Vita,ⁿ Jian Wang^o

- Resummation becomes essential when predicting observables containing widely separated scales
- Issues highlighted for future directions:
 - Resummation beyond the leading-power
 - Understanding jet substructure observables analytically
 - QCD studies with small-x resummation and connections to EIC physics

Snowmass 2021 whitepaper: Proton structure at the precision frontier

S. Amoroso,¹ A. Apyan,² N. Armesto,^{3,*} R. D. Ball,^{4,*} V. Bertone,^{5,*} C. Bissolotti,^{6,*} J. Blümlein,¹
R. Boughezal,^{6,*} G. Bozzi,⁷ D. Britzger,^{8,*} A. Buckley,^{9,*} A. Candido,^{10,*} S. Carrazza,^{10,*}
F. G. Celiberto,^{11,12,13,*} S. Cerci,¹⁴ G. Chachamis,¹⁵ A. M. Cooper-Sarkar,^{16,*} A. Courtoy,^{17,*} T. Cridge,^{18,*}
J. M. Cruz-Martinez,^{10,*} F. Giuli,^{19,*} M. G. Guzzi,^{20,*} C. Gwenlan,^{16,*} L. A. Harland-Lang,^{21,*}
F. Hekhorn,^{10,*} T. J. Hobbs,^{22,23,*} S. Hoeche,²² A. Huss,^{19,*} J. Huston,^{24,*} J. Jalilian-Marian,²⁵ M. Klein,²⁶
G. K. Krintiras,²⁷ H.-W. Lin,²⁴ C. Loizides,²⁸ G. Magni,^{29,30,*} B. Malaescu,^{31,*} B. Mistlberger,^{32,*} S. Moch,^{33,*}
P. M. Nadolsky,^{34,†} E. R. Nocera,^{4,*} F. I. Olness,^{34,*} F. Petriello,^{35,6,*} J. Pires,^{15,36,*} K. Rabbertz,^{37,*}
J. Rojo,^{29,30,*} G. Schnell,^{38,39,*} C. Schwan,^{40,*} A. Siódmok,^{41,*} D. E. Soper,^{42,*} M. Sutton,^{43,*}
R. S. Thorne,^{18,*} M. Ubiali,^{44,‡} G. Vita,^{32,*} J. H. Weber,^{45,*} K. Xie,^{46,*} C.-P. Yuan,²⁴ and B. Zhou^{47,*}

- PDFs tie together precision theory and experiment and are indispensable in all aspects of hadron collider physics
- Some of the highlighted future directions (see 2203.13923 for more a complete list):
 - PDF improvements from future Electron-Ion collider data
 - Getting ready for PDF fits at N₃LO
 - Incorporating theoretical uncertainties in PDF fits
 - Better understanding of transverse-momentum dependent PDFs

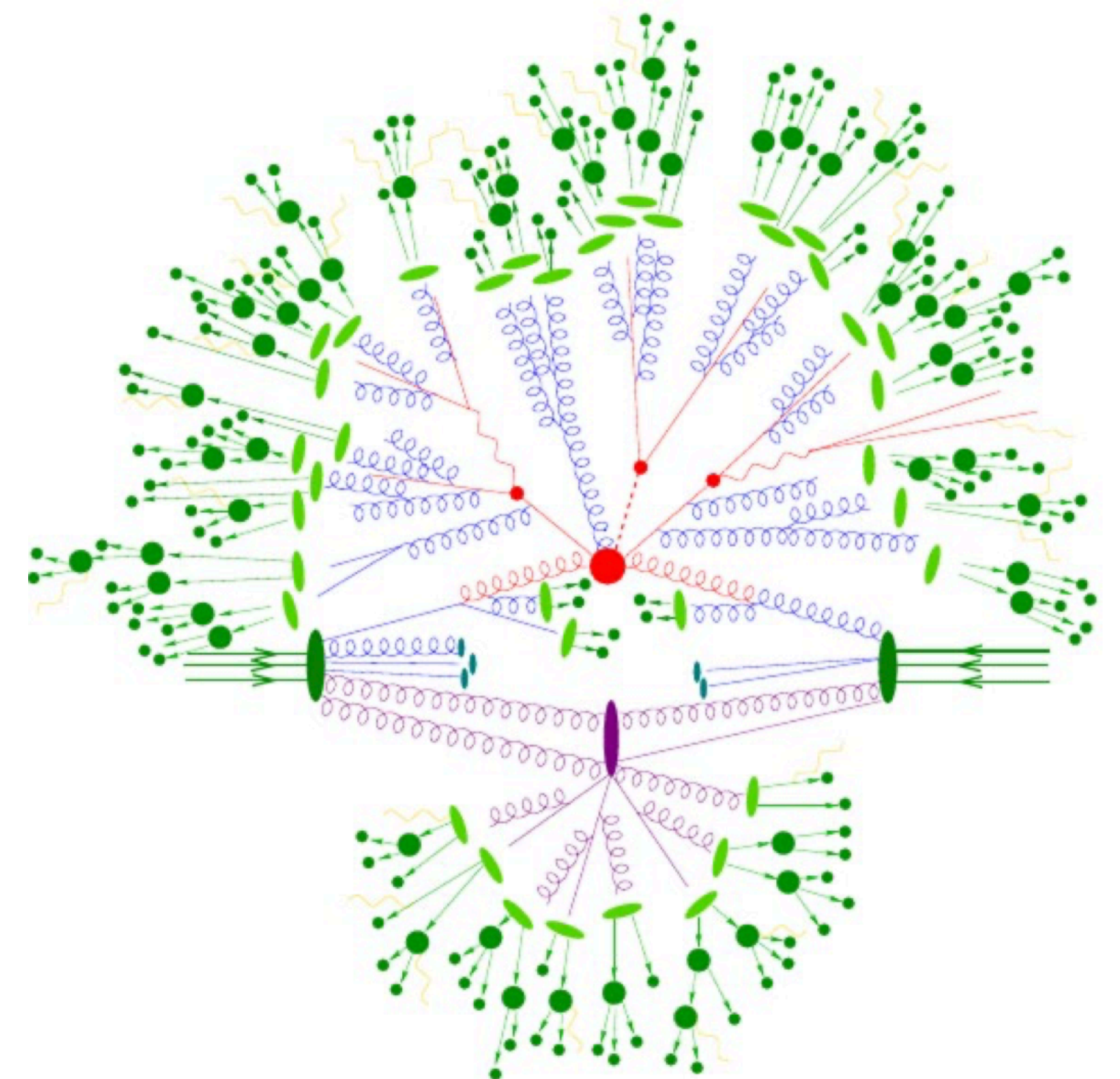


arXiv: 2203.13923

Future prospects for parton showers

Neda Darvishi^{1,2}, Joshua Isaacson³, M.R. Masouminia⁴, Zoltan Nagy⁵,
Peter Richardson⁴, Davison E. Soper⁶,

- Parton shower event generators play a central role in the planning and interpretation of experiments, and improving the approximations used within them is an active area of current research.
- **Issues highlighted for future directions:**
 - Matching to NNLO and beyond for $2 \rightarrow 2$ processes as well as high multiplicity processes
 - Going beyond the leading-color approximation
 - Assessing the accuracy of parton shower resummation
 - Including electroweak radiation in parton showers
 - Construction of parton showers with splitting kernels extended to α_s^2 (currently done with LO DGLAP)



Theoretical developments in the SMEFT at dimension-8 and beyond

Simone Alioli¹, Radja Boughezal², Weiguang Cao³, Mikael Chala⁴, Álvaro Díaz-Carmona⁴, Supratim Das Bakshi⁴, Gauthier Durieux⁵, Lukáš Gráf⁶,
Guilherme Guedes⁷, Brian Quinn Henning⁸, Teppei Kitahara⁹,
Hao-Lin Li¹⁰, Xiaochuan Lu¹¹, Camila S. Machado¹², Adam Martin¹³,
Tom Melia^{14*}, Emanuele Mereghetti¹⁵, Hitoshi Murayama¹⁶, Christopher
W. Murphy, Jasper Roosmale Nepveu¹⁷, Sridip Pal¹⁸, Frank Petriello^{19†},
Yael Shadmi²⁰, Jing Shu²¹, Yaniv Weiss²², Ming-Lei Xiao¹⁹, Jiang-Hao Yu²¹

- SMEFT is increasingly the framework used to understand the implications of data from the LHC and elsewhere for new physics constraints
- Focus of the white paper was on results beyond the leading dim-6 level
- Issues highlighted for future directions:
 - Interplay between RG running and positivity bounds at dim-8
 - Connections with UV models
 - Phenomenological implications of dim-8

New physics in B meson mixing: future sensitivity and limitations

Jérôme Charles*,¹ Sébastien Descotes-Genon*,² Zoltan Ligeti,³
Stéphane Monteil*,⁴ Michele Papucci,⁵ Karim Trabelsi*,² and Luiz Vale Silva*⁶

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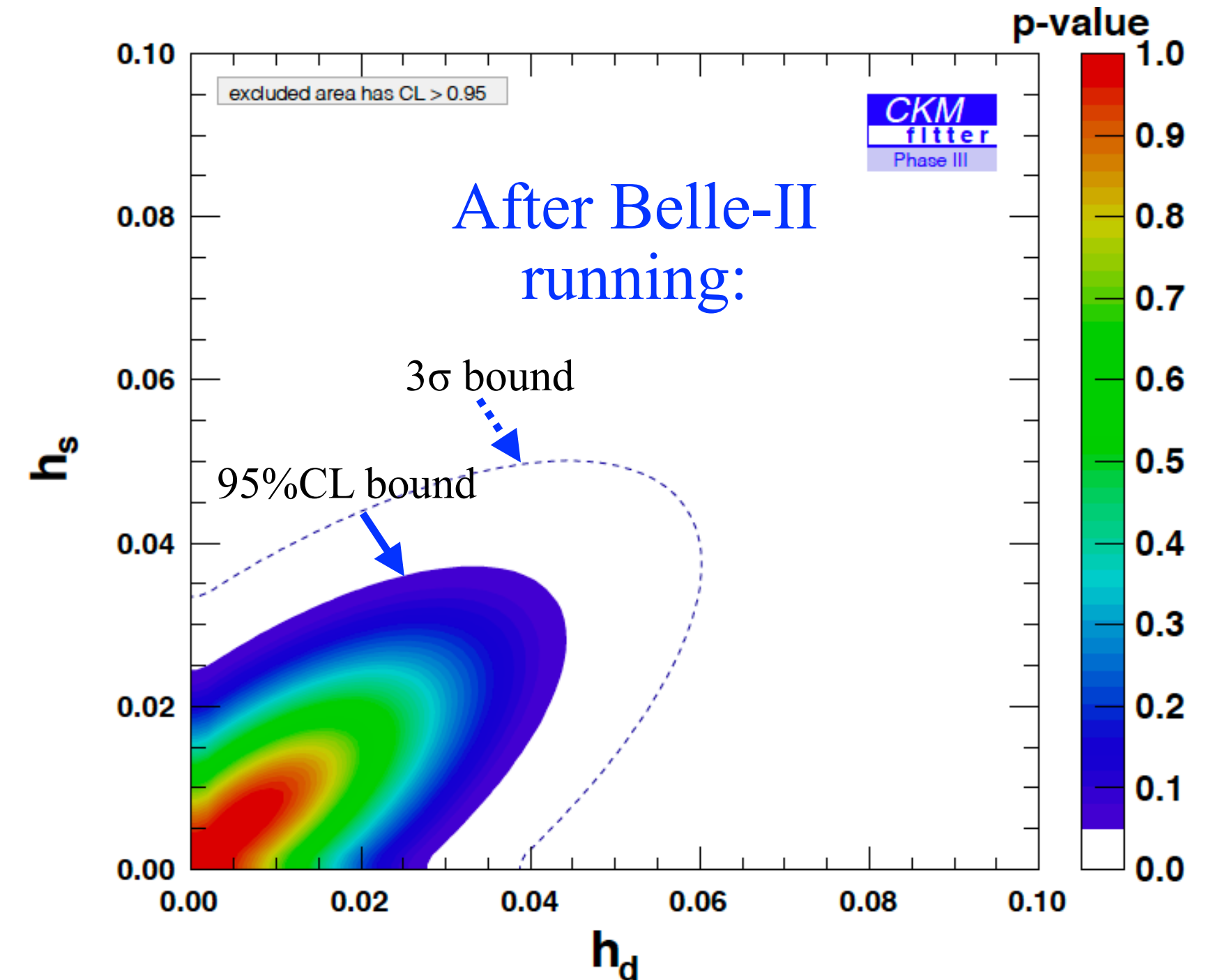
⁵*Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA*

⁶*IFIC, Universitat de València - CSIC, Parc Científic, Cat. José Beltrán 2, E-46980 Paterna, Spain*

**for the CKMfitter Group*

- The mixing of neutral mesons is sensitive to energy scales far beyond the direct reach of the LHC, and is a valuable tool in the search for new physics
 - Current measurements of B_d and B_s mixing from LHCb still allow ~20% new physics contributions
 - Excellent prospects for improvement in the future: Belle-II can improve these constraints by a factor of 3

Can probe energy scales
approaching 1000s of TeV!



$$M_{12} = (M_{12})_{\text{SM}} \times (1 + h_{d,s} e^{2i\sigma_{d,s}})$$

Advances in precision theory since the last Snowmass have opened the door to tests of the SM at levels previously unachievable. Many more developments are still needed.
An exciting time to work on this direction!

Today's TF06 session

- Looking forward to have a lively discussion in this session!
- The talks are a mix of white paper overviews and topics of current interest
 - Theoretical developments in the SMEFT beyond dim-6 (Frank Petriello)
 - Theory perspective on the W-mass (Josh Isaacson)
 - Precision measurements and field theory: a virtuous cycle (Isabel Garcia Garcia)
- The TFo6 report and a document for providing your feedback can be found in the following links:

Report link: <https://bit.ly/3cnOT2Y>

Feedback link: <https://bit.ly/3altHEc>

Thank you!